Auto-triggerable HPD sensors fully readout on Ethernet - applications for highs energy physics and medical imaging

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The OPERA project is dedicated to neutrino oscillation search in the CNGS neutrino beam from CERN to Gran Sasso [1]. The experiment is designed to characterize the interactions of ν_τ resulting of the $\nu_\mu \longrightarrow \nu_\tau$ oscillation.

The main element of the detector is a brick 10.2cm $\times$ 12.8cm cross-section consisting of 56 emulsion sheets 100μm wide interleaved with 1 mm lead plates. These bricks are assembled in walls of $\sim$ 7m side. A total of 72 walls is foreseen for the OPERA experiment with a total fiducial mass of 2 ktons.

When a neutrino interaction occurs the tracks of the charged particles are recorded in the emulsions with a high accuracy and the topology of the event is fully reconstructed with an automatic scanning of the emulsions. The role of the target tracker in OPERA is to locate the brick where the primary neutrino interaction occurs, to provide triggers and to make a coarser reconstruction of the events. It consists of 2 planes of scintillator strips located after a brick wall. The scintillation photons are collected by WLS fibers and read by a multi-pixels photodetector.

We present results obtained with 61 pixels HPD's readout by auto-triggerable front-end electronics of the VA-TA series. We have also developed a new kind of acquisition system based on Ethernet able to read the front-end electronics and deliver the data directly to the Ethernet network. The full readout chain from the scintillator to the DAQ has been tested with cosmics and with beams from the CERN PS.

The acquisition scheme is being proposed for the OPERA DAQ system and can be implemented for medical applications with various photodetectors. A prototype of micro- Positron Emission Tomograph (microPET) is being build on this scheme in collaboration with other Rhône-Alpes institues.

1 Ethernet DAQ system

Given the low data rate in OPERA, we completed a R&D on a fully based Ethernet acquisition scheme. The idea is to implement the concept of "smart sensors" on the experiment : a photodetector, readout by an auto-triggerable electronics (to be independant from any external trigger, beam spill etc) is accessible (for the configuration and the data transfer) directly from a PC with a single Ethernet link connected to the front-end card [2].

Such Ethernet capable front-end modules use a Ethernet device (Webplug or BFOOT 11501 from Agilent Laboratories) – a custom ASIC based on a 68000 microprocessor and the VxWorks real time kernel – containing an embedded Ethernet controller which includes a Web server and receives the data through a 5 Mbps link obeying the IEEE 1451.2 standard. This standard makes a partition into the Network Capable Application Processor (NCAP) and the Smart Transducer Interface Module (STIM, in our case a 12bit 25 MHz ADC and a sequencing element, FPGA of the type Altera APEX 20K200). The STIM provides all the features needed to control the analog front-end chip (VA-TA32cg) and is interfaced with the network by the NCAP. It is therefore accessible transparently.

The prototype designed and tested in Lyon (called ORCA for Opera Readout CArd) includes all the features to control the front-end (bias, shift-registers, configuration of the acquisition mode : single- or multi-channel, external or internal trigger, ADC frequency, data format, triggers counters etc) a time stamping of the trigger of the events (either the TA trigger or any external trigger).

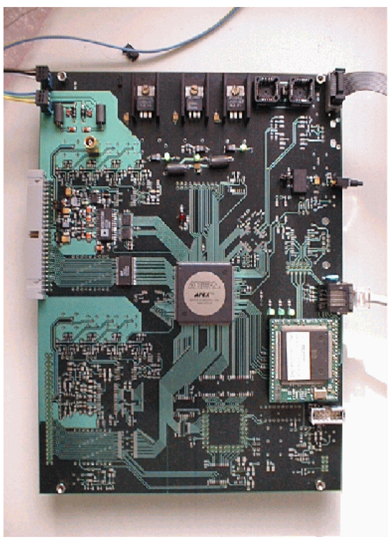

FIG. 1: The ORCA module

In a global scheme each front-end module is seen as a node in the network. Each node is accessible by typing an URL or by *http* commands or through a data streaming application which allows to keep a network connection opened and send the data continuously on Ethernet. A software interface using LabVIEW has alos been written to configure the system and get the data in a transparent way.

The system has been implemented during beam tests at the CERN PS in summer 2001 and proved to work in all the possible configurations. It is the first test of a full Ethernet capable readout chain. The success of these tests have brought a lot of interest on this kind of opto-electronics system which is very modular (for example the MaPMT 64 pixels of Hamamatsu is currently used in our system with a different type of VA-TA electronics, called VA32hdr11 - TA32cg). A first prototype of microPET is being build with MaPMT's, LSO and LuAp cristals and Ethernet front-end module. The first results are expected for summer 2002.

2 The front-end

The front-end electronics belong to the VA-TA family produced by IDEAS. The front-end electronics should overcome the problem of low gain of the HPD (typically 3000 corresponding to 0.5 fC for a single photo-electron) and should be fast enough to provide the trigger.

VA-TA's are multi channel chips, with charge-sensitive preamplifiers followed by a fast (TA : 75 ns peaking time) and a slow shaper (VA : 1-2 μs peaking time). Each channel in the trigger chip TA is followed by a level-sensitive discriminator with adjustable threshold, a serial shift-register to select the channels allowed to trigger and a monostable. In the VATAcg version a different threshold can be set for each channel. The outputs are ORed together and can be sent to the VA part. The OR then serves as a sample and hold signal for the charge accumulated at the VA part. The delay between trigger and hold matches the peaking time of the VA. The same OR signal can initiate the readout sequence. In the VA part, the outputs of the preamplifier enter a multiplexer. Its switches are controlled by a bit-register running in parallel. The output of the multiplexer goes to the output of the chip via a buffer. Only one of the channels is seen on the output at every readout step. The data can then be clocked into an ADC.

We have characterized the chips (either in test mode or connected to the HPD) in term of gain/noise performance, dynamic range, peaking time, pedestals and threshold spread.

The gain is measured in calibration mode. For the VA chip, the pulse-height is recorded. For the TA, a scan is performed over the threshold voltage range for a given injected charge. The threshold is found when the 50% trigger efficiency is reached. The mean value for the VA(TA) is around 120(-16) mV/fC and the gain spread/chip is around 2%.

The VA noise is found to corresponds to 500 e^- ENC. The TA noise is computed from the trigger efficiency curve. It is around 900 e^- ENC. The TA gives a trigger that is common for all the chip. The threshold is also set for all the TA channels. The channel-to-channel spread becomes a limitation when we are dealing with very low thresholds. To overcome this behaviour, a 3 bits DAC has been implemented in the chip to allow individual adjustment of the thresholds around the common value. The threshold spread is then reduced by a factor 3 after optimization of the bit-pattern in the DAC mask.

The VA dynamic range (around 25 p.e.) is insufficient and we are currently testing in the same the VArich chip with larger dynamic range (more than 200 p.e.).

3 HPD Characteristics

Detailed studies have been performed in Lyon using a 61 pixels HPD model, produced by DEP. The external dimensions of the HPD are 38 mm × 13 mm. The useful diameter of input window is 18 mm. The high voltage and ground connections use 2 wires on the side. The HPD tube is surrounded with a rubber coating for isolation. The input window lies $\sim$ 1 mm under the surface of this coating. This is useful for the connection of the fiber cookie with the input window without imposing strong constraints on the tube itself. The photo-cathode is deposited on a fiber optics entrance window. This gives very good performance for the HPD in terms of optical cross-talk. The photo-cathode is of multi-alkali S20 type. Each pixel is 2 mm side to side, with an active area of 3.5 mm^2. A depletion voltage of 60 V is required to fully deplete the silicon diode. The gap between 2 adjacent pixels is 50 μm and the electrical cross-talk is less than 1%. The output capacitance of the pixels is around 4 pF. Many tests have been completed to characterize the HPD in terms of : resolution, uniformity, linearity, cross-talk, dark current.

The HPD is plugged on a front-end board (9.5 cm × 12.5 cm) and kept in a metallic black box. The light coming from a blue LED (with an emission close to the maximum emission peak of the WLS fibers) can be distributed to the HPD either through a single 1 mm diameter clear fiber in contact with its entrance window or through a 61 pixels cookie matching the pattern of the HPD pixels. This permitted us measurements of the cross-talk with a fiber-to-photo-detector connection very close to the final design. In particular one has to a) minimize the distance between the entrance window plane and the cookie and

b) optimize the matching between the fibers and the HPD pixels.

HPD's are known to have excellent photon resolution, illustrated in Fig. 2 where the mean number of photo-electrons is 3 : at least 6 peaks are visible.

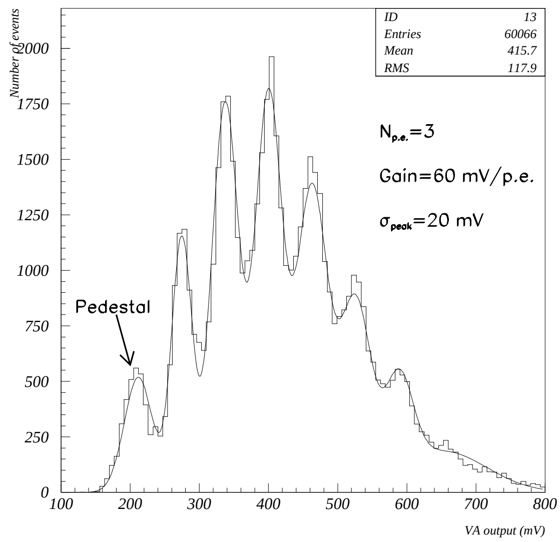

FIG. 2: Detailed spectrum of one of the neighbouring pixels.

We studied the evolution of the HPD gain as a function of the high voltage applied. The high voltage is varring between the value to separate the first photo-electron from the pedestal (5 kV) and 10 kV. The positions of the two peaks are given by the mean values of two gaussians. The theoretical gain slope is $1000/3.62 = 276.2$ e^- per kV and the result of the measurement obtained with a fitted slope is 268 e^- per kV which is an excellent agreement with the previous estimation.

The pixel-to-pixel gain uniformity is a clear advantage of the HPD. The uniformity is important for the front-end electronics design that has not to take into account the gain spread compensations. We measured the uniformity with the dark current spectrum for every pixel as explained previously. We operated in auto-triggerable mode with a threshold adjusted between the pedestal and the first photo-electron peak. The resulting gain non-uniformity, defined as $\sigma_{Q_{pe}}/\langle Q_{pe}\rangle$ is less than 5%.

We evaluated the optical cross-talk of the HPD by illuminating a pixel with a clear fiber in contact with the entrance window. The cross-talk is given by the fraction of signal received by the neighbouring pixels. The cross talk on the neighbouring pixels from the flashed pixel is not larger than 2% per pixel.

The corollary of the sensitivity at large wavelengths is the increase of the dark current (thermo-emission

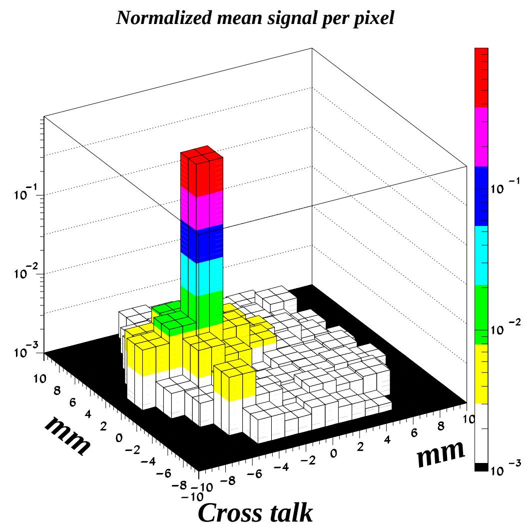

FIG. 3: 3-D view of the signal received by the HPD 61 pixels, normalized to the maximum signal. The maximum cross-talk signal is less than 2%.

of the photo-cathode). This dark current must be kept at a reasonable level in order to minimize the dead time in an auto-triggerable acquisition operating with a threshold of a fraction of photo-electron. Two different measurements have been performed to cross-check the dark current rate with the one given by DEP specifications. The first one is a direct measurement of the dark current spectrum in auto-trigger mode with a threshold below the first photo-electron. The limitation of such a measurement is the uncertainty on the trigger efficiency at any given threshold. A second measurement has therefore been performed with an external trigger by looking at random dark current counts occurring in correlation with the external trigger. Both measurements are consistent with a dark current rate around 25 kHz cm^{-2} or 1 kHz/pixel compatible with the DEP specifications (14 kHz cm^{-2}) given the uncertainties on the temperature conditions (the dark current may double every 5 degrees).

We believe that the new generation of low noise electronics is sufficiently well understood permitting us to tackle this problem with sufficient confidence.

4 PMT's and medical applications

In the context of Ethernet capable readout, we have validated our acquisition chain with MaPMT. It has 64 independent channels and each pixel covers a surface of 2.3×2.3 mm^2, there are also two series of 12 dynodes. A double grid of focalization electrodes separates the PMT channels while a single electrode separates the two dynode openings of the same channel. An output from each channel is provided.

This PMT is read with a VA-TA card and the acquisition is done on ethernet. The calibration of the PM is done and we have calculated the gain for each channel. This gain is well adjusted by relation ; $G = \beta \times HV^{\alpha}$. The figure 4 shows the distribution of the two parameters. The mean value for α is 10 with a spread of 0.4 (4%). For β, the mean value is 4680 with a spread of 290 (6%).

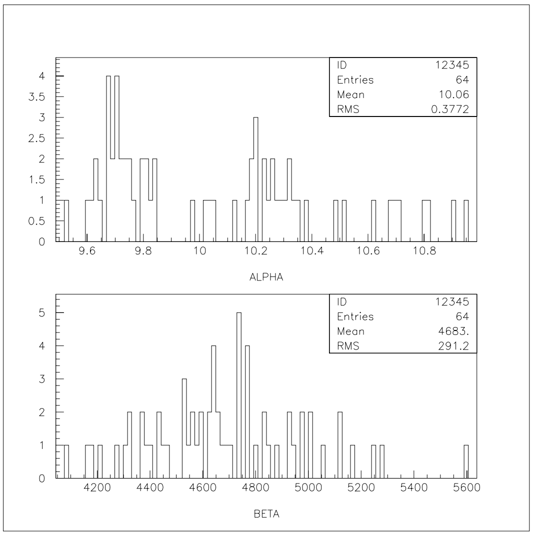

FIG. 4: Distribution of the two parameters used for the fit of the gain values.

The calibration of the PMT is done with a pulsed LED. Figure 5 shows the spectrum when there are 2 photo electrons as mean value. The positions of the pedestal and of the peaks are obtained with a dedicated function. The pedestal position is obtained by a gaussian and an exponential functions. The latest function is needed due to the upper part of the pedestal which is not gaussian. The position of the photo electrons are obtained by a gaussian function and the high of these peaks is calculated with a poissonian function. The mean number of photo electrons obtained with this method is 2.003.

The single photo electron level can also be accessible with this acquisition and with the VA-TA. Figure 6 shows the distribution for 1 photo electron. The parameters of the fit are calculated as indicated previously. This method can be used to calibrate the PMT and to fixe a threshold at a level lower than 1 photo electron (1 third of photo electron as example in OPERA).

The PMT will be used in medical applications as micro pet and we obtained the first results with crystals. We can reconstruct the spectrum of a photon hitting the crystal and the PM.

This adaptable acquisition (auto triggerable electronics and Ethernet acquisition) can be used, to characterised photodetector and as well in high energy

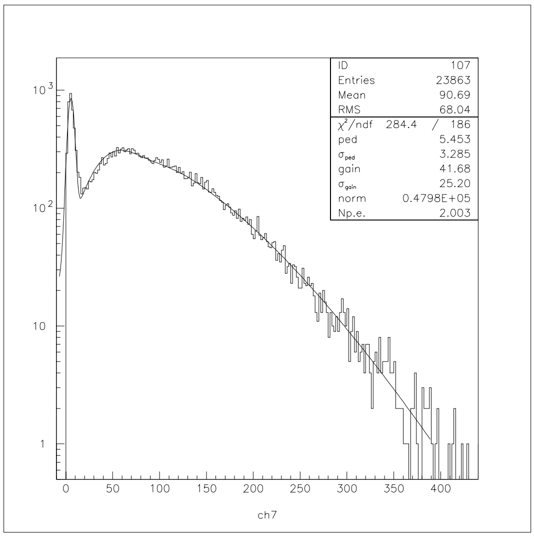

FIG. 5: 2 photo electrons spectrum.

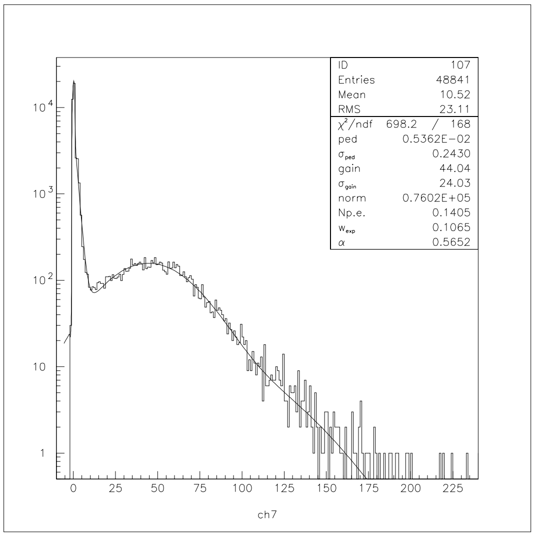

FIG. 6: 1 photo electrons spectrum.

experiment and in medical applications.

Références

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[2] "Ethernet network-based DAQ and smart sensors for the OPERA long-baseline neutrino experiment", C.Girerd, S.Gardien, J.Burch, S.Katsanevas, J.Marteau